# Emission spectrum from an Al/Mg tracer in the blow-off region of a radiatively ablated capsule*

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A study of X-ray emissions from Al/Mg tracers buried at two different depths in a plastic shell is presented. The X-rays originating from the K-shell transitions of the Al/Mg ions begin to irradiate after the ablative heating wave has passed through the trace layer and are recorded with a streaked crystal spectrometer. Only emissions from the capsule with the trace layer buried at a smaller depth are observed. Hydrodynamic simulations and a collisional–radiative model including detailed atomic physics are used to investigate the measured spectrum. It is found that the effects of the radiative heating play important roles in the formation of the K-shell emission. The time correlation between the simulations and the measurements is obtained by comparing the measured time profile of the He $\alpha$ emission with the calculated one. The line ratio of Ly $\alpha$ to He $\alpha$ is also calculated and is found to be in fairly good agreement with the experimental data. Finally, the relation between the time profile of the He $\alpha$ emission and the ablation velocity is also discussed.

**Keywords:** inertial confinement fusion, X-ray diagnostics

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## 1. Introduction

In the research of indirectly driven implosion, the laser energy is directed into a high-$Z$ hohlraum to produce a thermal radiation field, which is then used to ablate the capsule surface. The radiative ablation process generates very high pressure and causes the capsule to implode inward. As mentioned in Ref. [1], the energy needed for ignition is closely related to the ablation pressure. It is also known that increasing the ablation velocity will reduce the Rayleigh–Taylor instabilities.[2] So it is important to study the issues related to the radiative ablation. Usually, the radiative ablation can be characterized by quantities like the ablation velocity, the ablation pressure and the plasma conditions in the ablation region. In theoretical studies, various scaling laws of the ablation velocities and the ablation pressure have been derived.[3] The effects of the ablations by non-local thermal equilibrium (non-LTE) radiation and of the preheating by hot electrons or M-band emissions have also been addressed in numerical simulations.[4] In experimental studies, the ablation velocities were deduced from the plane target experiments,[5,6] in which time-resolved resonant line emissions were observed. A similar idea is used to design our experiment in the context of indirectly driven radiative ablation. By placing trace layers at different depths, we expect that the time interval of the onsets of the resonant line emissions from different trace layers could be used to infer the ablation velocity. An attempt is made in our work to characterize the plasma conditions in the ablation region via the emission spectrum of the trace layer. The plasma is heated by the radiation field, which is also significant for astrophysics.[7] When X-rays ablate the capsule surface, a shock wave is lunched, which is followed by an ablative heat wave. The shock wave compresses the trace layers and heats them to the temperature of 10 eV. This temperature is too low for the K-shell emission to be observed. However, there is a quick rise in the temperature of the trace layer on the arrival of the ablative heat wave. After that, the trace layer is heated to the temperature of the radiation source and begins to irradiate the K-shell emissions. These emissions are then recorded and modeled to provide information about the radiatively ablated plasma.

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## 2. Experimental setup and results

The experiments discussed here were carried out at the Shengguang II laser facility. The capsule (Fig. 1) was made of a 100-μm inner radius 2-μm wall thick glass microballon coated with a 9-μm thick CH layer. The trace layer, which consisted of Al and Mg with an atomic number ratio of 3:7, was then buried in the CH ablator at different depths. In our experiments, two formal depths of 2 μm and 6 μm from the capsule surface were adopted. The capsule was filled with 10 atm $D_2$ and was placed in the centre of a gold hohlraum, which was 1500 μm in length and 800 μm in diameter. The incident laser energy was directed into the hohlraum and was converted into X-rays to radiatively ablate the capsule. The radiation flux was monitored by a soft X-ray spectrometer (SXS) viewed through the laser entrance hole. The effective radiation temperature was then deduced from the measured radiation flux and a peak temperature of 190 eV was observed. Diagnostic holes were opened on each side of the hohlraum to observe the emissions of the blow-off plasma, which was dispersed with an polyethylene terephthalate (PET) crystal onto the streak camera.

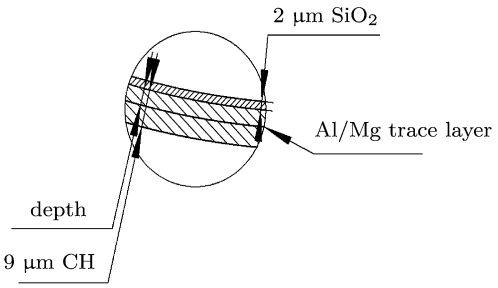



**Fig. 1.** Illustration of the capsule. Two depths of trace layer were used in our experiments.

As shown in Fig. 2, K-shell emissions in a range from 1.3 keV to 2 keV have been recorded with a time resolution of 30 ps. The experimental result shown in the figure was observed by using the capsule with a trace layer of 1.8 μm depth. We have identified the resonant lines of Mg He $\alpha$, He $\beta$, Ly $\alpha$, Al He $\alpha$ and Al Ly $\alpha$. The Mg He $\beta$ line is located at the red wing of the Al He $\alpha$ line and blends with the Al Li-like satellites under current spectral resolving power. This limits the use of the Mg He $\beta$ line as a diagnostic signature. Only the emissions from Al ions are analysed in our work. We use a Gauss function to fit the measured line profile, under which the area should represent the line intensity. The Al He $\alpha$ emission intensity (denoted with solid squares in Fig. 3) is extracted by integrating the measured spectrum in 150 ps at different times. The start point of the integral is chosen as the He $\alpha$ emission becomes observable. The line ratio of Ly $\alpha$ to He $\alpha$ (denoted with solid squares in Fig. 4) is also extracted by integrating the measured spectrum in 300 ps to obtain a good signal-to-noise ratio. We failed to observe the K-shell emissions by using the capsule with a trace layer of 6.4 μm depth. The reasons for this will be discussed in the following section.

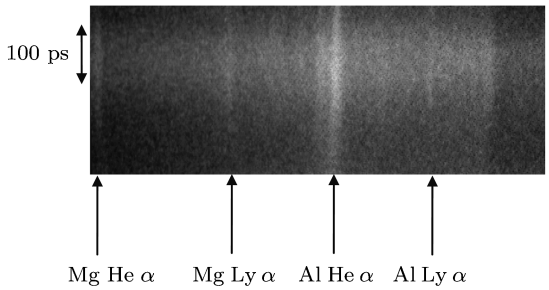



**Fig. 2.** Image obtained with a streaked crystal spectrometer. This image was observed by using a capsule with a trace layer of 1.8 μm depth.

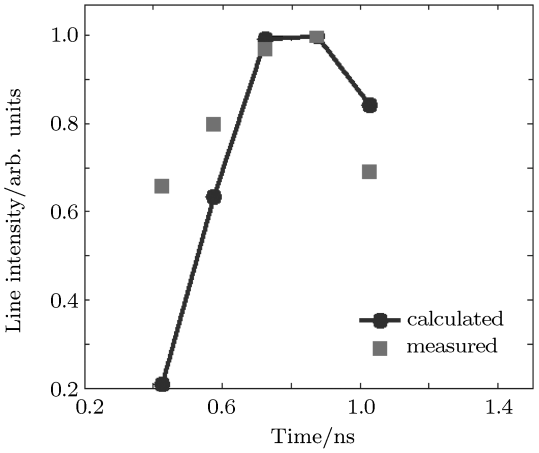



**Fig. 3.** Comparison between the measured emission intensities of Al He $\alpha$ line and the calculated ones, from which relative timing is established.

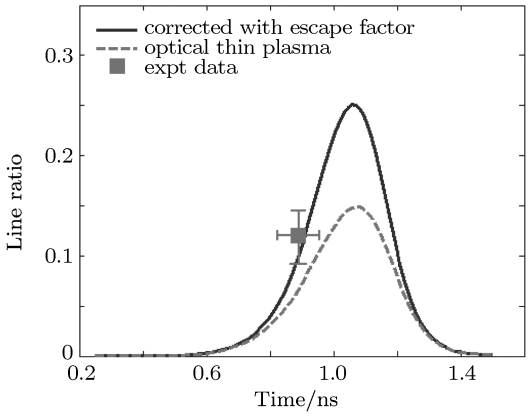



**Fig. 4.** Comparison between the measured line ratios of Ly $\alpha$ to He $\alpha$ (square) and the calculated ones.

## 3. Data analysis

We now discuss the modeling of the measured results. First, the time histories of the temperature and the density in the trace layer due to the hydrodynamic motion are calculated by using the MULTI-1D code.[8] Next, by post processing the time histories of the temperature and the density, the evolutions of the level populations are calculated by the non-LTE collisional-radiative model[9,10] in the steady state approximation. Finally the modeled line ratios are compared with the experimental results with relative timing established by matching the time profiles of the He $\alpha$ line intensity. The measured line ratio cannot be well explained unless the photon processes are included in the non-LTE calculation, which implies the importance of the radiation heating in the blow-off plasma formation.

In modeling the time histories of the temperature and the density in the trace layer, the measured radiation temperature with the soft X-ray spectrometer is used as an input. For the simplicity of the level population calculation, the radiation temperature ($T_\mathrm{r}$), the electron temperature ($T_\mathrm{e}$), and the electron density ($N_\mathrm{e}$) in each calculation grid in the trace layer are mass weighted and are plotted in Fig. 5 for the case of the capsule with a trace layer of 1.8 μm depth. As shown in Fig. 5, the trace layer is compressed and remains at low temperature before the arrival of the ablative heating wave. However, there are a sharp rise in temperature and a decrease in density after the arrival of the heating wave. After that, the trace layer is heated to follow the temperature of the radiation source.

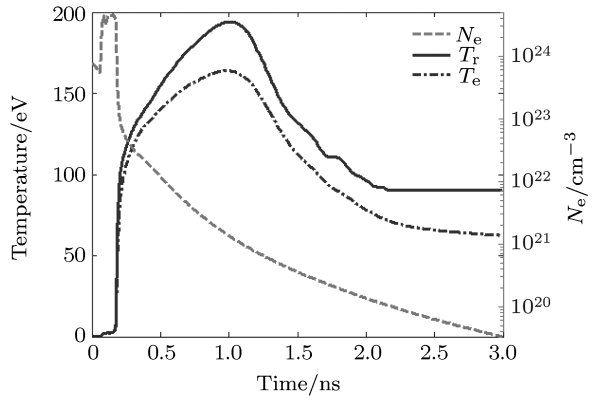



**Fig. 5.** Simulated time histories of mass-weighted radiation temperature, electron temperature and electron density for the trace layer in a depth of 1.8 μm.

With these hydrodynamic parameters, the ionization balance in the trace layer is calculated with the non-LTE collisional–radiative model at each time step. Various atomic processes are considered, including the electron impact excitation, the ionization, the radiative recombination, the three-body recombination, the dielectronic recombination and so on. The Planck radiation field is assumed and is characterized with simulated mass-weighted $T_\mathrm{r}$. The effects of the radiation field on the ionization balance are then investigated in our study by turning on or off the photon processes, such as the photon ionization and the photon excitation. The results are shown in Fig. 6. As we can see, the line ratios of Ly $\alpha$ to He $\alpha$ increase remarkably when the photon processes are turned on, which implies that the average charge state is increased.

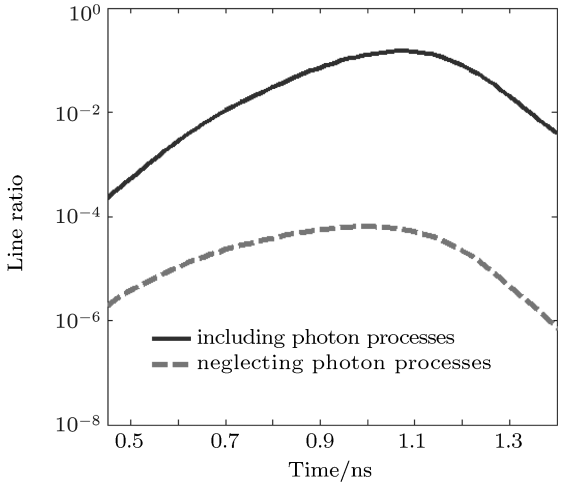



**Fig. 6.** Time evolution of line ratio of Ly $\alpha$ to He $\alpha$. A comparison is made between the results including and neglecting the photon processes.

Before comparing the measured line ratios with the calculated ones, the relative timing of the simulations to the measured results must be established. This is achieved by comparing the measured time profile of the He $\alpha$ emission with the theoretical calculated one. The calculated time profile is integrated in 150 ps as we have done in the analysis of the measured result with a selected start point of integration. As we vary the start point, a best match of the calculated profile to the measured one is found. The accuracy of this method for finding time correlation depends on the sensitivity of the start point selection and is estimated to be 60 ps. In Fig. 3, we show a matched case corresponding to the trace layer of 1.8 μm depth. The

effects of self-absorption are corrected with the escape factor before we compare the calculated line intensities to the measured ones. We have noticed that there is a discrepancy between the two time profiles. It may be attributed to the preheating of the ablators by the M-band radiations according to Ref. [4]. Since the M-band radiations, which have longer absorption lengths, can penetrate more deeply than the heating wave and lead the materials in front of the heating wave to be heated in some early time.

With the relative timing established above, we compare the measured line ratio with the calculated one in the case of a trace layer of 1.8 μm depth, as shown in Fig. 4. The effect of self-absorption is corrected with the escape factor.[11] We expected to have more than one experimental points when the radiation temperature approached to its peak value. However, the fact that the back ground noise increased to a very high level at the time of the peak radiation temperature made the signals to be unobservable. Anyway, the experimental data have been well explained by our calculation.

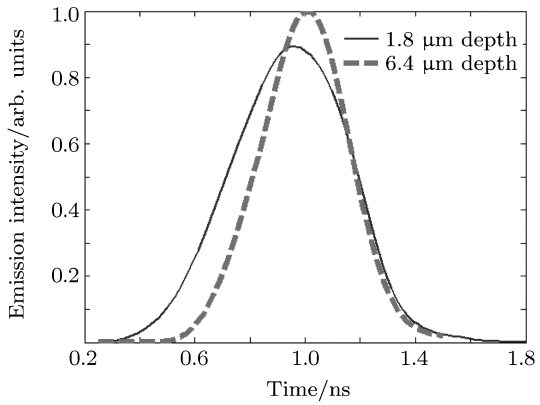



**Fig. 7.** Time histories of Al He $\alpha$ emissions for different trace layer depths. The profiles are calculated under the assumption of optically thin.

At the end of the analysis, we will briefly discuss the relation between the time profiles of the resonant line emissions and the ablation velocity. In the first place, it was thought that the ablation velocity could be diagnosed by observing the different rising time of certain resonant line emissions from the trace layers buried at different depths. However, as shown in Fig. 7, we can see that the rising edges of the He $\alpha$ emissions are not sharp enough for a clear time indication and do not have the same increasing rate. It will become more ambiguous when the instrumental uncertainty is taken into account. So the ablation velocities cannot be related to the time profiles very well, which means that the original designs of these experiments should be re-examined carefully. As we mentioned before, we fail to observe the K-shell emissions by using the capsule with trace layer of 6.4 μm depth. However, the simulated results show that the intensities of the He $\alpha$ emissions have the same magnitude in both cases and the peak value in the case of 6.4 μm depth is even larger than that of the other one. The discrepancy between the simulations and the measurements still exists even when we take into account the effect of the self-absorption by the escape factor. There is still one possible way out of current difficulty according to the measured background noise, which stays at a very high level. The more deeply the trace layer is buried, the smaller the time interval between the onset of the trace layer emission and the stagnation of the imploding shell is. Once the hot spot is formed, it becomes bright and emits intensive X-rays that could be too intensive and cover the experiment signal. Anyhow, further work is needed to interpret this experimental result.

## 4. Conclusion

In this paper, we study the emissions from a trace layer buried in an ablator. Line ratios and line intensities, which to some extent represent the ionization balance, are analysed. Although we fail to record the line emissions from the deeper trace layer, the measured line ratio is well matched by the calculation result when the photon processes are considered. It is also found that the ionization degree of the trace layer closely follows the variation of the radiation temperature. This fact implies the potential use of the line ratios to characterize the radiation temperature of the blow-off plasma and to study the influence of the hot electron and the M-band emission on the capsule. We also conclude that the time profile of individual line emission does not closely follow the change of $T_{\rm r}$ in the ablator when the radiative heating wave is passing through it. So using the time behaviour of the line emissions to diagnose the dynamics of the radiation ablation should be performed very carefully.

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